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# Policies and Deployment for Fuel Cell Electric Vehicles An Assessment of the Normandy Project

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Abstract:

The paper provides a cost benefit analysis of one of the most prominent deployment project in France of fuel cell electric vehicles, taking place in Normandy. The project builds on the substitution of a diesel Renault Kangoo by an electric Renault Kangoo ZE with a fuel cell range extender for public fleets. The analysis points out potential weaknesses of the project as it is envisioned today using a decomposition of the value-chain. To achieve sustainability in 2025 a much stronger deployment should take place. This would allow for a sharp decrease in the total cost of ownership thanks to a close coordination between hydrogen production and its delivery through refilling stations to take advantage of the expected increasing volume of hydrogen consumption along the deployment path. This suggests that a high level in public funds at this early deployment phase can be critical for the success of the project.

JEL classification: D04, H54, L91, Q55

Key words: fuel cell electric vehicles, cost benefit analysis, public policies, infrastructure

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1. Introduction

A number of studies suggest that the deployment of fuel cell electric vehicles (FCEV) will increase at a modest rate until 2030 at best (McKinsey & Company, 2010; Rösler, van der Zwaan, Keppo and Bruggink, 2014; Zachmann, Holtermann, Radeke, Tam, Huberty, Naumenko and Faye, 2012; Oshiro and Masui, 2014). Indeed the current deployment of FCEV remains in its infancy relative to BEV (Tietge, Mock, Lutsey, and Campestrini, 2016). Still some early FCEV deployments are taking place in various countries (Brunet, Kotelnikova and Ponssard, 2015). The Normandy project is the most prominent one in France. This paper provides an assessment of this project.

The geographical deployment of battery electric vehicles (BEV) proceeds through clusters in large suburban areas, and then expects to expand through corridors that would connect these clusters. This is bound to be even more so for the deployment of FCEV for three reasons: (i) the potential regional markets will be initially low because of the high price of the vehicle,[2] (ii) this means many regional markets will be required to achieve a minimum efficient size for vehicle manufacturing, (ii) on each regional market the infrastructure will require large investments with low profitability in a hydrogen distribution network due to the initial low volumes of H2 consumption. On the contrary, in countries with a well-developed electrical network, the cost of BEV terminals is relatively low. There is no need for specialized maintenance.

These considerations points out the complementarity of direct and indirect consumer subsidies with infrastructure subsidies has been the key driver for the deployment of BEV,[3] Norway being the ideal case study (Tietge, Mock, Lutsey, and Campestrini, 2016).

The analysis of the Normandy project provides an opportunity to see how these general considerations are at work and the role of public policies in the deployment. In Normandy a voluntary hydrogen plan has been designed and gained large political support. In terms of FCEV it builds on the substitution of a diesel Kangoo by an electric Kangoo ZE with a fuel cell range extender for public fleets. This hybrid solution delivers a vehicle with a range of 300 km (instead of 120km for the battery electric Kangoo ZE) for a lower cost than a full hydrogen vehicle. The whole value chain is reviewed in details: the hydrogen production cost by electrolysis or SMR, the distribution and the delivery costs of hydrogen, the manufacturing and running cost of the hydrogen Kangoo. The total cost of

[2] The price of the Toyota Mirai is around k€66 in Europe.

[3] This is known as the chicken-egg-dilemma. On the one hand, vehicles manufacturers need refilling stations to attract consumers and, on the other hand, infrastructure builders need vehicles. This chicken and egg situation would typically be solved through vertical integration (see for instance Bresahan and Levin, 2012). When the players are in different industries, such as it is the case for FCEV, vertical integration is unlikely to occur, inducing a delay in simultaneous investments.

ownership (TCO) is compared with the cost of the corresponding diesel vehicle. The amplitude of the public policies that results from this analysis, i.e. how much consumer incentives and infrastructure subsidies would be needed to make the TCO's comparable, is compared to the amplitude of existing policies. Measuring the gap at the 2025 horizon provides an interesting assessment for the potential success of the Normandy project, i.e. what are the chances that it will turn into a self-sustainable project or that it will remain highly dependent on political support. It is shown that, in the scenario envisioned today, the gap is quite substantial. A number of suggestions are made to alleviate this gap.

The paper is organized as follows. Section 2 gives the background for the Normandy project. The cost benefit analysis is carried out in section 3. This section provides the methodology, the main hypotheses, data sources, and details our results. Section 4 draws the implications in terms of sustainability of the project and the amplitude of the public support to achieve this sustainability. Section 5 concludes and suggests some further research.

## 2. The Normandy project

### 2.1 Normandy and the appealing factors for a Hydrogen Plan

The most ambitious project concerning hydrogen for mobility in France is the Normandy project. This project aims to install the utilization of hydrogen for a long term on the territory. The Manche department, which has some specificity, initiated it: the production of electricity is much larger than its consumption, and the difference is expected to grow further, moreover this electricity production is carbon free. There are currently two nuclear plants (REP) which produce 18TWh per year and a wind farm (0,2TWh). Two new nuclear plants are planned for 2017 and 2035 for an additional production of 13TWh by 2050. This area also presents a high potential for renewable energy sources (RES) from wind power (offshore and onshore) and from sea power (wave and sea flows). More than 24 TWh could be potentially produced by 2050 by RES. The Manche consumption is currently estimated at 14TWh per year. It will probably decrease with the energies efficiencies targets. Despite of the high electricity overproduction, Normandy imports 9 TWh of fossil resources for transport and heating.

In this context, the hydrogen solution has some appeal. Firstly, it decreases the import bill of fossil fuel and indirectly decreases the greenhouse gas emission. Secondly, instead of directly exporting the electricity overproduction, the production of hydrogen by electrolysis allows adding a value on the final product. Indeed, hydrogen may be used in several downstream markets including chemicals (such as methanol) and transport. It is also a possible way to store electricity produced by renewables. The development of the hydrogen energy vector is expected to increase local employment and attract highly qualified workers.

The project has gained much political support and been extended from the Manche department to the whole Normandy region.

## 2.2 The Hydrogen Normandy FCEV Project (EasHyMob)

The Normandy project is known as the EasHyMob project.[4] The project is coordinated by Symbiofcell, Normandy Region and Serfim. It covers the 2016-2018 time horizon. Symbiofcell is a private company that designs and produces kits to extend autonomy of full electric vehicles. The project has been built with the support of EHD2020 which is an association founded under the hospices of the Council of the Manche department that gathers more than 40 members including industrial companies, local counties and universities to promote the hydrogen plan in Normandy.[5] The project received the support of the European Innovation and Networks Executive Agency (INEA).[6] INEA allocated M€5 subsidy with a target deployment of 15 HRS of 350 bar with a capacity between 20 kg/day and 50 kg/day. Only public entities are eligible for these subsidies. Another constraint imposed by INEA concerns the location of the stations. They need to be close to the highways and that at least 15 hydrogen vehicles be on roads at the opening of a station.

At the end of 2014 a first hydrogen refilling station (HRS) 350 bar of 40kg/day had been installed to initiate the deployment of hydrogen vehicles. In 2016, there were 17 hydrogen vehicles on roads, of which 12 Hydrogen Kangoo and 5 Hyundai ix35 FCell. The HRS station can feed between 50 and 100 light duty vehicles (Hydrogen Kangoo), somewhat less full power vehicles as Hyundai ix25 FCell.

## 2.3 The Hydrogen Kangoo

The Hydrogen Kangoo is a BEV Kangoo ZE with a fuel cell range extender. The hydrogen device is composed of a fuel cell of 5kW and a tank of 1.8 kg of $H_2$ under 350 bar. The lithium ion batteries give a range of 120km and the hydrogen kit an extra 180km, so that a total range of 300km is available in urban cycle. The power of the fuel cell is low; it is used is to recharge the battery to increase the range.

SymbioFCell produces the fuel cell, Michelin (IMeca) assembles the hydrogen kit (fuel cell, tank, converter, etc.) and Renault (Renault Tech) installs the device on the Kangoo ZE. The deployment began at the end of 2014; in 2016, there were around 70 Hydrogen Kangoo on French roads.

[4] (http://www.ehd2020.com/wp-content/uploads/2015/09/Presentation-EAS-HyMob-16-July-2015.pdf).
[5] http://www.ehd2020.com/les-membres/
[6] INEA is the successor of the Trans-European Transport Network Executive Agency (TEN-T EA). One of the missions of INEA is to ensure the cohesion, interconnection and interoperability of the trans-European transport network.

The cost of the Hydrogen Kangoo is k€36,3 (VAT excl.): k€19.2 for the Kangoo ZE and k€17 for the hydrogen kit. In France, an ecological bonus of k€6,3 is allocated to such a green vehicle so that the purchasing net price is at k€30.

A version of Hydrogen Kangoo with a tank under 700 bar is now available and begins to be deployed in UK, Germany and North European Countries (Denmark, Norway, Sweden).

## 3. A cost benefit analysis of the Normandy project

### 3.1 Methodology, main hypotheses and data sources

Our cost benefit analysis of the Normandy project builds on the following methodology and main hypotheses:

- The cornerstone of the project is the substitution of a Diesel Kangoo (noted as D-K) by a Hydrogen Kangoo (to be denoted as H2-K) for a number of public fleets;
- The whole value chain of this substitution is reviewed in details: the hydrogen production, the distribution and the delivery of hydrogen, the manufacturing of the H2-K;
- The time horizon goes up to 2025, close enough to be meaningful for policy analysis and far away enough to assess the potential success of the project;
- Two scenarios are investigated: scenario 1 reflecting a moderate success under which the project would still rely on public subsidies and scenario 2 reflecting a full success under which the project becomes self-profitable; the initial position in 2016 is also modelled as a reference;
- The occurrence of each scenario depends on the internal deployment of the H2-K in Normandy but also on how successful the whole deployment of FCEV in France and possibly elsewhere in Europe takes place; we identify the main critical interfaces of this dependence;
- For each scenario our objective is to identify the total cost of ownership of both vehicles and the corresponding carbon abatement cost in 2025; then to use these results to assess the potential amplitude of public policies at that horizon and their optimal combination.

The data is coming mostly from interviews of the different actors of the Normandy project:

- For the characteristics of the Hydrogen Kangoo and the projections of its deployment in Normandy: SymbioFCell, EHD2020.
- For the characteristics of the electrolysis technologies and of the hydrogen retail stations: Air Liquide, GNVert, Keolis, Siemens, Areva H2gen, SERFIM, Tenerrdis, EHD2020, FCH-JU.
- For estimates of the electricity prices: RTE and EDF publications.
- For the scenarios: scenario 1 is based on the Actis bee study extended to the whole region, scenario 2 should be considered as our own construction to achieve sustainability in 2025

### 3.2 The scenarios

The scenarios are described Table 1. For each scenario estimates of the total park (sedan, utility, trucks, coaches ...), the penetration rate of H2 within the total park, and the number of H2-K are given. From these estimates the H2 consumption can be derived as well as the corresponding elements of the value chain: H2 production, retail stations (HRS), logistics. Table 1 gives the optimal design along the value chain for each scenario: how and where the hydrogen is produced (centralized or 1 or several sites, eventually on site at the hydrogen retail station), how it is delivered to the retail stations in case of centralized production.[7] It is assumed that electrolysis production of H2 is fully implemented in 2025 while in 2016 H2 is still obtained through the steam reforming process (SMR).

Table 1: The scenarios, the associated value chain and the cost benefit analysis

| | | | 2016 | 2025 | |
|---|---|---|---|---|---|
| | | unit | Current situation | Scenario 1 | Scenario 2 |
| Vehicles | Hydrogen fleet | # | 50 | 5 000 | 10 000 |
| | Penetration rate | % | 0,003% | 0,261% | 0,521% |
| | of which $H_2$-K | # | 40 | 2 000 | 4 000 |
| | Penetration rate in light duty vehicles | % | 0,013% | 0,67% | 1,34% |
| Production | Production technology | "" | SMR | Electrolysis | Electrolysis |
| | H2 production process | "" | Centralised | Centralised on 2 sites | on-site |
| Distribution | HRS capacity | kg/j | 20 | 100 | 400 |
| | Nb of HRS | # | 5 | 50 | 25 |
| | HRS utilization rate | % | 50% | 80% | 100% |
| | storage | "" | gas bottle | Tube Trailer | NC |

The scenario for 2016 corresponds to the deployment scheduled in the EasHyMob project for the end of 2016. The hydrogen is produced by Steam Methane Reforming in refinery. This system is centralized with a distance refinery-station of average 200km. The hydrogen is stored in gas bottle under 220 bar and delivered by trucks. The utilization rate of the retail stations is of 50%.

Scenario 1 should be considered as the most probable continuation of the EasHyMob project. It assumes that the project is fully realized in 2018 and continues on the same trend until 2025. The hydrogen is produced in two high powered electrolysers and the average distance electrolyser-station is 100 km. Hydrogen is stored on the station in 400 kg tube trailers. The utilization rate of the retail stations is of 80%.

Scenario 2 is our construction and should be considered as a sustainable target. The scenario assumes that EasHyMob project is fully realized in 2018 and accelerates in the following years. The hydrogen is produced on-site by electrolysis. The utilization rate on the retail stations is of 100%. Altogether the carbon abatement cost of this scenario has to be in line with a reasonable carbon price.

[7] The detailed calculation that leads to the optimal design can be obtained from the authors upon request.

For each scenario we shall establish a total cost of ownership in €/km adding the various cost components along the value chain. All costs are in € 2016 and no inflation is introduced. Capital expenditures will generate yearly expenses using an annual discount rate taken at 6%. Introducing the total cost of ownership for the D-K and its CO2 emissions per km allows for deriving the implicit carbon abatement cost. This remains a static analysis and a more detailed dynamic analysis would certainly been worthwhile. Still the figures we obtain give an idea of the cost benefit of the substitution of the H2-K versus the D-K.

### 3.3 The H2 electrolysis production cost in 2025

The main differences between the two scenarios may come from three factors:

- A higher power needed for centralized than for decentralized on site production;
- A lower utilization rate for scenario 1 than for scenario 2;
- A lower electricity price with centralized than for decentralized production.

Table 2 gives the detailed calculation to arrive at the hydrogen production by kg. [8] The first factor does not make much difference since in both cases the size of the electrolyser is high enough to allow for substantial economies of scale. A capex of 500 /Kw is assumed in both cases, based on the proton exchange membrane (PEM) technology. The second factor makes scenario 1 somewhat more costly than scenario 2 but this is overbalanced by the third factor that is the lower price of electricity in scenario 1. The rationale for this lower price comes under our assumption that the network fees are not supported in scenario 1 since the electrolysis sites would be connected directly to the production of carbon free electricity, which is more difficult to be achieved when hydrogen production is located in retail stations. It is assumed that both electricity prices exclude the CSPE (Contribution au service public de l'électricité).[9]

Altogether it turns out that there is no significant difference in the unit cost of production. However we shall see shortly that the mode of production has a major impact on the delivery cost.

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[8] In all Tables numbers in italic are obtained from the raw data reported in regular characters.

[9] This consumer tax compensates the electricity producers for the constraints imposed by the regulator such as buying back electricity produced through renewables at feed-in tariffs or providing electricity to low income households. Some consumers such as production of hydrogen through electrolysis have been granted exclusion for the tax. *“https://www.edf.fr/entreprises/le-mag/actualites-du-marche-de-l-energie/evolution-de-la-contribution-au-service-public-de-l-electricite-cspe-au-1er-janvier-2016”*

Table 2: The production cost of hydrogen in both scenarios

| | Simplified data sheet | unit | scenario 1 | scenario 2 |
|---|---|---|---|---|
| HRS capacity | | kg/day | 100 | 400 |
| Nb HRS | | # | 50 | 1 |
| PEM | daily working period | h/day | 12 | 12 |
| | Process efficiency | % | 76 | 76 |
| | Whole installation efficiency | % | 72 | 72 |
| | equivalent hydrogen energy | Kwh | 39 | 39 |
| | electricity needed by kg of hydrogen | Kwh/kgH2 | *54* | *54* |
| | Installation power needed | Kw | ***11 280*** | ***1 810*** |
| | Unit cost | €/kW | 500 | 500 |
| | Capex of electrolyzer | k€ | ***5 640*** | ***905*** |
| | Installation and grid connection | %Capex | 10 | 10 |
| | Storage infrastructure Capex | €/kg of capacity | 500 | 500 |
| | Opex of electrolyzer | %Capex | 3,5 | 3,5 |
| | lifetime | years | 15 | 15 |
| | utilization rate | % | 80% | 100% |
| | annual production | kg/year | ***730 000*** | ***146 000*** |
| | electricity price | €/Mwh | 50 | 65 |
| | **hydrogen production cost** | **€/kg H2** | ***4,0*** | ***4,5*** |

## 3.4 Distribution network and logistics

The number and capacities of the HRS depend on the scenario, which also determines the number of production sites hence the distribution network. Table 3 provides both the cost of a HRS for each scenario and the associated transportation cost to deliver H2 to the HRS network. The overall network average cost per unit of hydrogen consumed appears extremely high in 2016, because of low volumes. For scenario 1 the average cost is still significant so that the amplitude of public financing of the network remains an important question to study. For the scenario 2, the use of on-site production eliminates the transportation cost and thanks to the high consumption volume, the cost of the refilling station is low.

Table 3: The logistic cost of hydrogen in both scenarios

| **Logistics** | | 2016 | 2025 | |
|---|---|---|---|---|
| **Retail station** | | | scenario 1 | scenario 2 |
| capacity | kg/day | 20 | 100 | 400 |
| Capex | k€ | 200 | 150 | 1 000 |
| Opex | %Capex | 6% | 4% | 4% |
| installation | %Capex | 10% | 10% | 10% |
| lifetime | years | 15 | 20 | 20 |
| utilization rate | % | 50% | 80% | 100% |
| H2 delivered | kg/yr | ***3 650*** | ***29 200*** | ***146 000*** |
| **HRS cost** | €/kg | ***9,1*** | ***0,3*** | ***0,9*** |
| | | | | |
| **HRS utilization rate** | | | | |
| Hydrogen storage | | gas bottles | tube trailer | on site |
| Rentale rate for storage | €/month | 70 | 1 700 | NC |
| subcontracting cost for transport | €/km | 1,2 | 2 | |
| Delivery distance | km | 200 | 100 | |
| HRS capacity | kg/j | 20 | 100 | |
| Utilization rate | % | 50% | 80% | |
| Quantity delivered / Trucks | kg | 50 | 400 | |
| **Transport cost** | €/kg | ***10,7*** | ***4,4*** | ***0*** |

### 3.5 The total cost of ownership and the implicit carbon abatement cost

To complete the cost benefit analysis one needs to introduce the manufacturing cost of the H2-K, the lifetime of a vehicle, the number of kilometres it runs per year and the fraction of which it operates on the fuel cell extender. This is done in Table 4. In this Table similar assumptions are also introduced concerning the D-K (manufacturing cost, fuel efficiency and diesel price).

These values allow for the derivation of the total cost of ownership (TCO) and the calculation of the implicit carbon abatement cost. For scenario 1 the abatement cost is estimated to be 536 €/tCO2 which is much higher than the normative cost of carbon suggested by economic studies (see for instance Quinet 2013). This should not lead to a negative appraisal of the Normandy project as long as one considers that a full deployment could be achieved some years later. For instance one could interpret scenario 2 as the projection of scenario 1 in 2030. Since scenario 2 delivers an almost sustainable assessment of the project (with a 100 €/tCO2 in 2030 as proposed in Quinet 2013), the static abatement cost obtained for 2025 of the deployment trajectory corresponding to scenario 1 should be taken as an intermediary result that does not reflect the full benefit of the scenario.[10]

[10] The interested reader is referred to Creti, Kotelnikova, Meunier and Ponssard (2015) for a methodology to derive a relevant proxy of the abatement cost in the case of a progressive deployment of a green technology. One could expect that this proxy would generate a lower

Table 4 : The cost benefit analysis of the H2-K relative to the D-K.

| **Simplified data Sheet** | Unit | 2016 | 2025 | |
|---|---|---|---|---|
| **Scenarios** | # | | 1 | 2 |
| Annual driving distance | 1000km/yr | 35 | | |
| lifetime | yr | 7 | | |
| **Manufacturing cost** | | | | |
| Hydrogen kangoo purchase cost | k€ | 36,3 | 31,3 | 22 |
| | €/km | ***0,18*** | ***0,15*** | ***0,11*** |
| Diesel kangoo purchase | k€ | 10 | | |
| | €/km | ***0,05*** | ***0,05*** | ***0,05*** |
| **Yearly Maintenance cost** | | | | |
| Hydrogen kangoo | k€/year | 0,7 | | |
| | €/km | ***0,02*** | ***0,02*** | ***0,02*** |
| Rental fee of the battery | €/month | 90 | 50 | 30 |
| | €/km | ***0,03*** | ***0,02*** | ***0,01*** |
| Diesel model | k€/year | 1 | | |
| | €/km | ***0,03*** | ***0,03*** | ***0,03*** |
| **Vehicle cost** | | | | |
| Hydrogen Kangoo | | ***0,23*** | ***0,19*** | ***0,14*** |
| Diesel Kangoo | | ***0,08*** | ***0,08*** | ***0,08*** |
| **Fuel Cost** | | | | |
| **Hydrogen Kangoo** | | | | |
| Hydrogen production cost | €/kg | ***1,5*** | ***4,0*** | ***4,5*** |
| station distribution cost | €/kg | ***9,1*** | ***0,3*** | ***0,9*** |
| Transport cost | €/kg | ***10,7*** | ***4,4*** | ***0,0*** |
| Hydrogen Delivery cost | €/kg | ***21,3*** | ***8,7*** | ***5,4*** |
| Hydrogen kangoo consumption | kgH2/100km | 1 | 1 | 1 |
| Range done by Hydrogen | km | 180 | 180 | 180 |
| Electricity Consumption | Kwh/100km | 18,3 | 18,3 | 18,3 |
| Range done by electricity | km | 120 | 120 | 120 |
| Fuel cost hydrogen kangoo | €/100km | 13,54 | 5,93 | 3,58 |
| | €/km | ***0,14*** | ***0,06*** | ***0,04*** |
| **Diesel Kangoo** | | | | |
| Diesel cost | €/L | 1 | 1,1 | 1,2 |
| Diesel consumption | L/100km | 7 | 6,65 | 6,3 |
| Fuel cost Diesel kangoo | €/100km | ***7*** | ***7,315*** | ***7,56*** |
| | €/km | ***0,07*** | ***0,07*** | ***0,08*** |
| **Total Cost of Ownership** | | | | |
| TCO Hydrogen kangoo | €/km | ***0,36*** | ***0,25*** | ***0,17*** |
| TCO Diesel kangoo | €/km | ***0,15*** | ***0,15*** | ***0,15*** |
| **CO2 emissions** | | | | |
| Hydrogen Kangoo | kgCO2/100km | 5,9 | 0 | 0 |
| Diesel Kangoo | kgCO2/100km | 18,90 | 17,96 | 17,01 |
| **Carbon abatement cost** | €/tC02 | ***1 647*** | ***536*** | ***108*** |

abatement than 536 €/tCO2 since at this date one could still expect a significant decline in the TCO of the H2-K if scenario 1 converges to scenario 2 in 2030. This methodology cannot be directly applied here since we have not modelled the deployment trajectory from 2016 to 2030.

Our analysis of the value chain decomposition allows for a quantification of its different components and provides an important result. As shown in Figures 1 and 2, for the $H_2$-K user, the two main sources of cost are the vehicle cost (Capex stands for yearly equivalent investment cost and Maintenance for maintenance of the vehicle) and the fuel cost. Both of these sources are expected to significantly decrease but the order of their magnitude will change. As one goes from 2016 to scenario 1 and scenario 2 learning by doing and spill overs should explain the decrease in the vehicle cost.[11] This will depend on the Normandy project but also, and probably more, on what happens to the deployment of the Hydrogen Kangoo and its fuel cell components at the European level. As for the fuel cost our analysis points out that the decrease in cost results from the much higher volume of hydrogen consumption in scenario 2 and the corresponding joint optimization between production and networking. This suggests that a close coordination is required to optimize along the value chain to translate the progressive increase in consumption into cost benefits through on site production. In terms of amplitude, as long as the coordination is efficient, the decrease in the fuel cost is more significant than the decrease of the vehicle cost that is 75% versus 40%. While the two components are almost of the same order of magnitude in 2016, in scenario 2, the vehicle cost is now about three times more costly than the fuel cost.

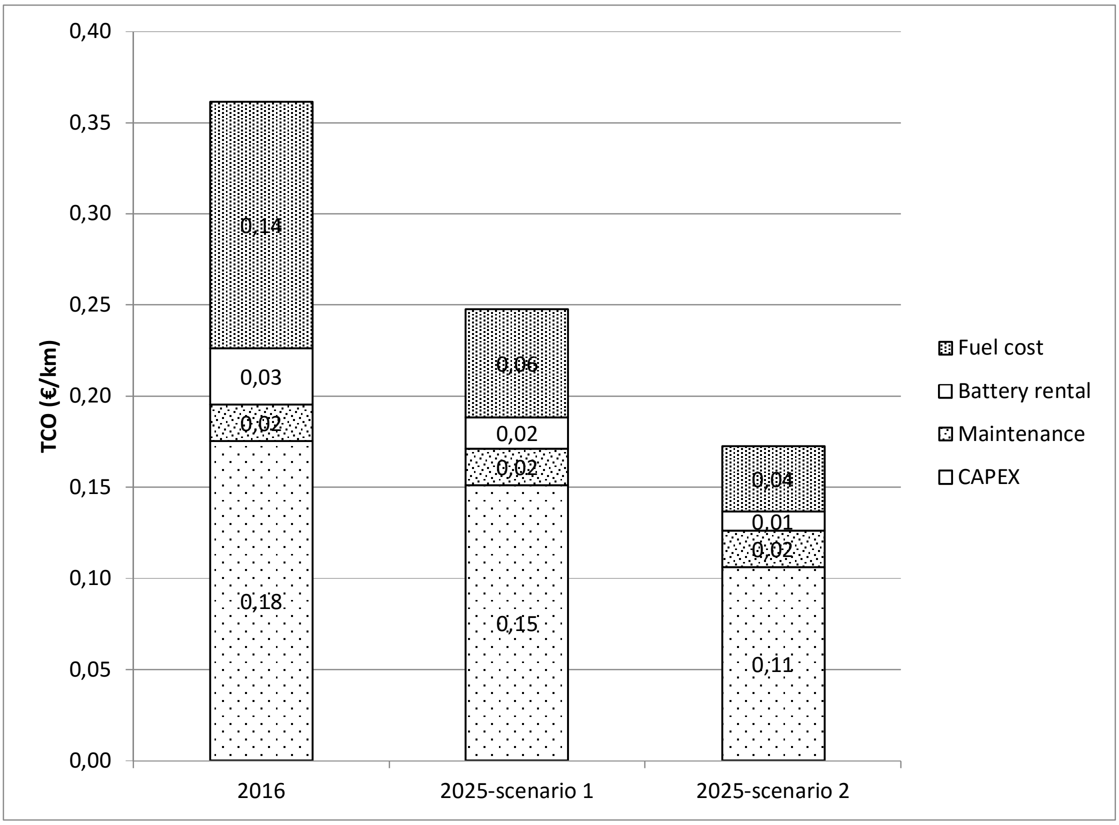


*Figure 1: H2-K TCO decomposition*

[11] See for instance Schoots, Kramer and van der Zwaan (2010) for an analysis of learning by doing in FCEV.

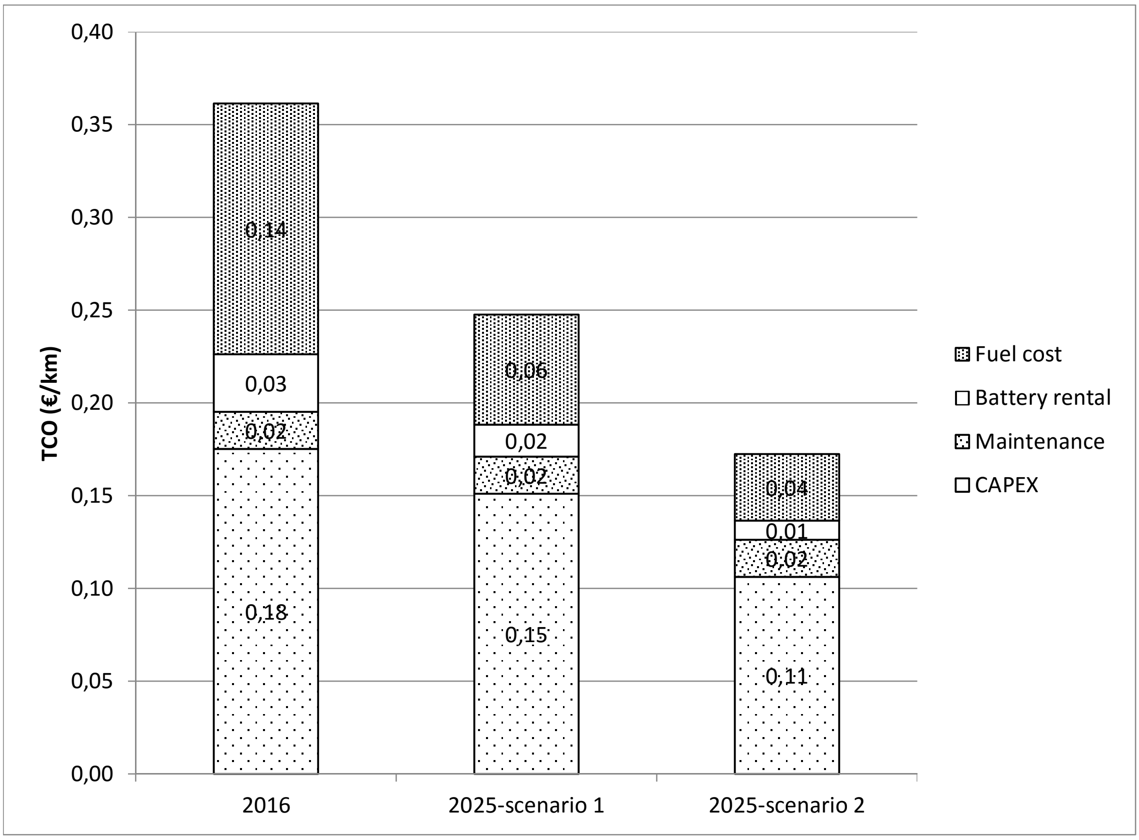


*Figure 2: Hydrogen cost decomposition*

4. Discussion: how to achieve sustainability for the Normandy project

This cost benefit analysis provides interesting insights for the design of policies to promote the deployment of H2-K in Normandy. It allows for a quantification of the global amplitude of the public support that the project would still require in 2025, through a comparison between scenario 1 and scenario 2 taken as a target for sustainability.

We construct a target policy for scenario 1 in 2025 such that the TCO for the H2-K would be equal to the TCO for scenario 2. More precisely we assume that a difference of approximately 650 €/year (the difference in TCOs times the km/year) for a public fleet user of a H2-K relative to a D-K is acceptable given its indirect ecological benefits on top of a carbon abatement cost of the order of 100 €/tCO2. Table 5 describes this target policy. It is based on a subsidy of the infrastructure cost in line with the level of current subsidies that is at 70% of the incurred capital costs. Then the rebate on the vehicle price is derived; we can see that a substantial rebate of k€12 is required. The unit subsidies are translated into a yearly average amount that takes into account the lifetime of each component; this gives approximately M€11 per year. This gives an idea of the total yearly budget that should be obtained at the regional, national and EU levels.

Table 5: the target public policy

| Target subsidies | full unit cost € | € or % subsidy per unit | # of units | average subsidy k€/year |
|---|---|---|---|---|
| Rebate on vehicle | 31 300 | 12 000 | 5 000 | 10 140 |
| Electrolyser capex | 5 640 | 70% | 2 | 767 |
| HRS capex | 150 | 70% | 50 | 432 |
| Transport cost (rental truck) | 1,7 | 70% | 72 | 86 |
| total subsidies | | | | 11 424 |

We may now compare the target policy with the current subsidies that have been obtained in 2016. Today, there are several organizations supporting the FCEV Deployment in France by investing in HRS (FCH-JU, Ademe, Feder, INEA) and vehicles (FCH-JU, France, Ademe). Assuming that these subsidies would be expended to 2025 at the same level (i.e. remain identical in percentage values) we may simulate their impact on the TCO. They would translate into a 6 300 rebate for the vehicle cost and a 70% rebate on the capex of HRS. Table 6 synthesizes such a policy. The annual yearly subsidy would be at M€5.7 that is approximately half our target budget. With such a subsidy the annual over cost of a H2-K would be €2300, which is substantial. The annual yearly subsidy should also be compared with the subsidy obtained by the project for 2016-2018 namely k€850. Our hypothesis that subsidies would remain constant up to 2025 is highly questionable.

Table 6: An extrapolation of the current policy for 2025

| Target subsidies | full unit cost € | € or % subsidy per unit | # of units | average subsidy k€/year |
|---|---|---|---|---|
| Rebate on vehicle | 31 300 | 6 300 | 5 000 | 5 323 |
| Electrolyser capex | 5 640 | | 2 | - |
| HRS capex | 150 | 70% | 50 | 432 |
| Transport cost (rental truck) | 1,7 | | 72 | - |
| total subsidies | | | | 5 755 |

Altogether we consider that the gap between our target policy and the current policy is quite large. This suggests that the Normandy project will remain dependent on the regional and national political support for the coming years unless circumstances are such that scenario 2 materialize in 2025.

## 5. Concluding comments and suggestions for further research

Our analysis of the deployment of the Normandy project delivers several important results. We modeled the situation in 2016, made projections for 2025 based on current assessments and constructed a target scenario for which sustainability is achieved (sustainability being defined as delivering an implicit carbon abatement cost of 100€/t CO2). This scenario could possibly be obtained in Normandy in 2030 or earlier if circumstances are highly favorable. According to our cost benefit analysis the TCO of the Hydrogen Kangoo would need to be reduced by a half along this path. Through a detailed examination of the value chain we showed that there are two requirements to achieve this goal.

The first requirement assumes a significant level of learning by doing and spill overs in the manufacturing of the Hydrogen Kangoo to allow for a 40% decline of the purchase price of the Hydrogen Kangoo vehicle. This can only be consistent with a success of FCEV deployment in two dimensions: (i) geographic that is not only in Normandy but all through Europe, (ii) across an extended line of H2 vehicles that is not only for Kangoo but also through sedan, buses and trucks so that altogether a large increase of the hydrogen volume of consumption is generated in Normandy. The initial network should be viewed in this perspective. To achieve this objective, high power vehicles (buses, trucks...) have an important role to play. [12]

The second requirement concerns a close coordination between hydrogen production and its delivery through refilling stations to take advantage of the increased volume of hydrogen consumption and manage the progressive substitution of steam methane reforming (SMR) by electrolysis. More specifically we evaluated the two optimal designs (associated with centralized production versus on site production) that should constitute the successive stages of the optimal path for infrastructure. A successful coordination strategy would allow for a 75% decrease of the hydrogen fuel cost.

We then compared our sustainable target with the most probable scenario for 2025 and calculated the amplitude of public support that would be needed to make affordable the deployment of Hydrogen Kangoo for consumers. Assuming that a difference of 650 € per year would value the indirect benefits we showed that there is a substantial gap between the required level of subsidies and the subsidies obtained for years 2016-2018. This suggests that a strong political support for the Normandy project is needed for a much longer period.

Our analysis points out further that while the level of subsidies for infrastructure is much less important than the level of direct subsidies for consumers the path followed in the infrastructure deployment can be critical to achieve sustainability. This calls for some questions as regards the options followed by the Normandy project: the current project focuses on the Hydrogen Kangoo which implies some technical choices in terms of tanks and HRS (350 bar) and indirectly for small HRS (because of low hydrogen volumes since the Hydrogen Kangoo is a hybrid). These options, relevant given the economic context, may actually make difficult our transition to sustainability (based on 700 bar and large HRS associated with high consumption volumes). It would be interesting to explore further the possible dead ends arising from these options and suggests possible ways to move along the lines suggested by scenario 2. This highlights the short term gains of scenario 1 and its potential long term risks. Alternatively a large deployment as expected in scenario 2, such as seems to be the case in Germany, would make the profitability of the early HRS deployment more risky while generating higher gains in the future. This would be worth exploring further a systematic year-by-year dynamic analysis.

It would certainly also be worthwhile to explore this question more formally. Our analysis suggests that the two cost components (vehicle and fuel costs) involved in the deployment of FCEV could be formalized as follows. The vehicle cost component would involve learning by doing generating a decreasing unit cost over time. The fuel cost component would involve convexities generating an increasing marginal cost at any point

[12] This is in line with Farrell, Keith and Corbett (2003), which suggested focusing the deployment on heavy duty freight modes.

of time. The dynamic interaction between these two components would be such that a lower vehicle cost generates a lower fuel cost and vice versa, the first effect being much stronger that the second one. It would be interesting to formalize further such a joint cost function and discuss its implication in terms of policies and deployment.

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